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RAMM-TM for Canister Gas Leakage Detection and Radiological Consequences

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Background and Introduction

- This presentation describes work performed under a Cooperative Research and Development Agreement (CRADA) between Argonne National Laboratory and the Central Research Institute of Electric Power Industry (CRIEPI), Japan.

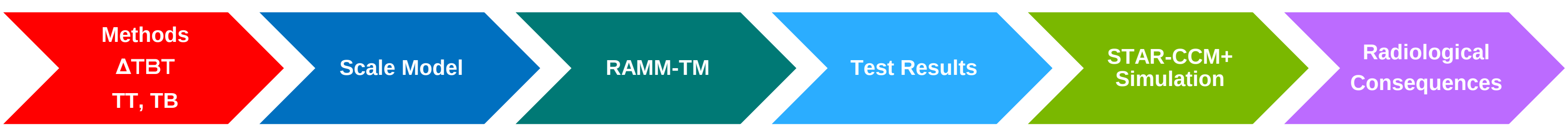
- This presentation includes results published in 2 NED journal papers in 2021:

  – Monitoring of helium gas leakage from canister storing spent nuclear fuel: Radiological consequences and management, Nuclear Engineering & Design 382 (2021) 111391.

  – RAMM-TM for detection of gas leakage from canisters containing spent nuclear fuel, Nuclear Engineering & Design 385 (2021) 111534.

- Aging management – detection of aging effects – inspection and monitoring

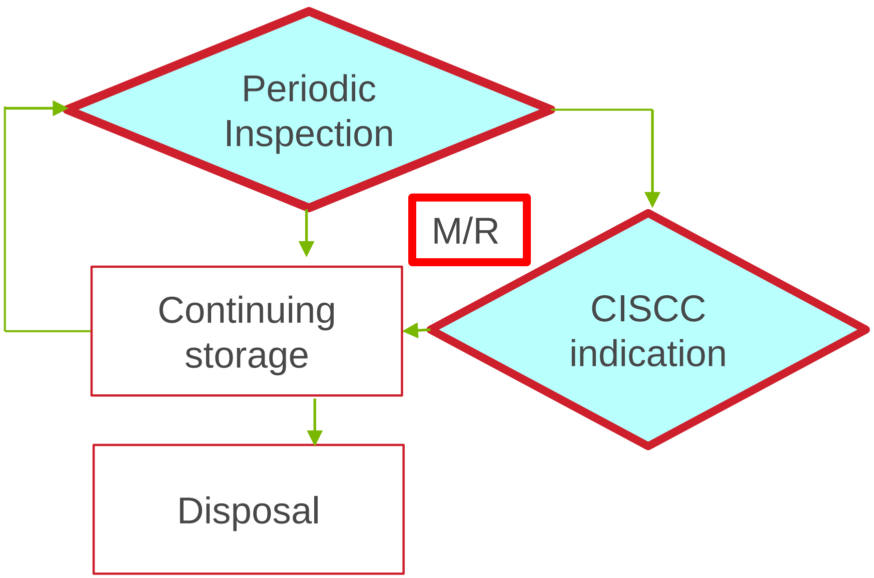
- Outline of Presentation

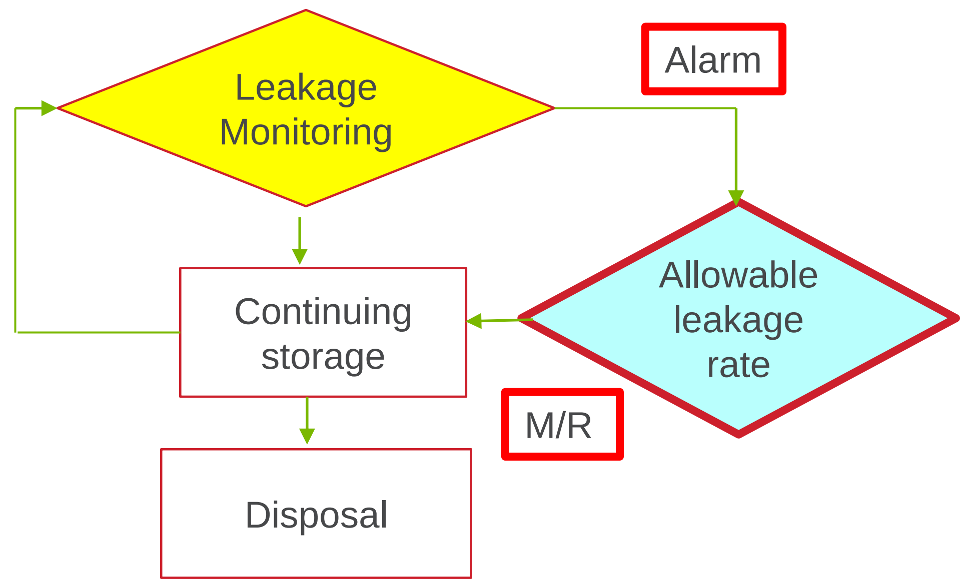


Ageing Management - Inspection/Monitoring

- Periodic inspection of selected canisters
- Mitigation & repair (M/R), if CISCC indication found
- Costly and labor-intensive

- Continuous monitoring of many canisters
- M/R before exceeding allowable leakage rate
- Cost-effective and reduce risks to public safety, health, and environment.





Canister Helium Leakage Detection Methods

ΔTBT Method

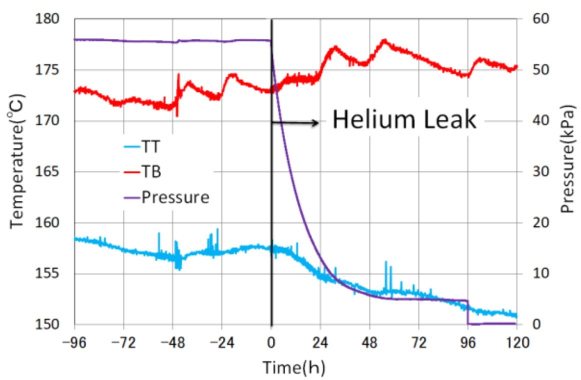
Temperature difference between TT and TB. NED Vol. 238 (2008)

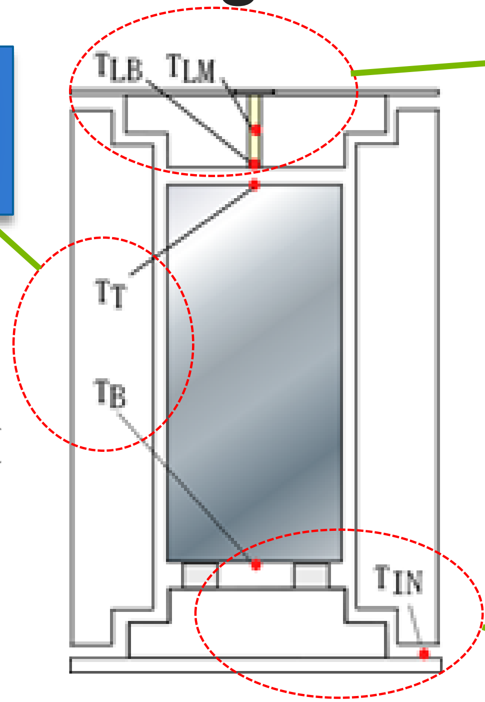
TT Method

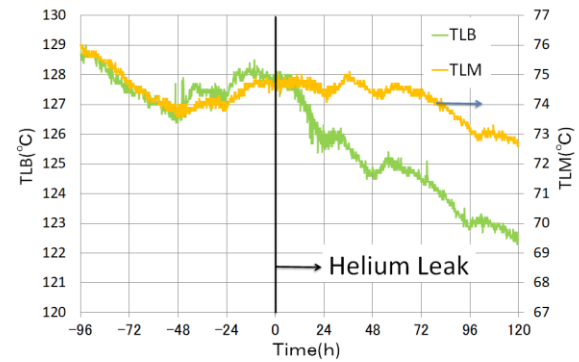
Temperature difference between TLB and TLM. NED Vol. 352 (2019)

TB Method

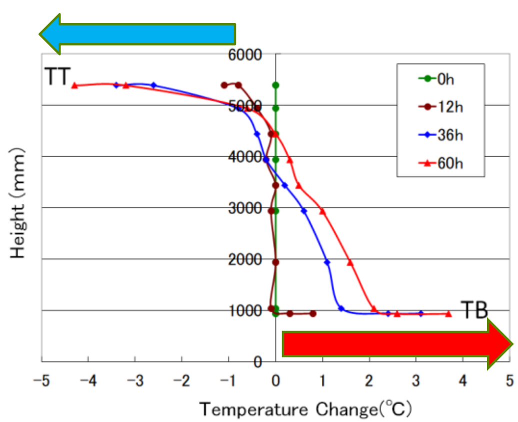
Temperature difference between TIN and TB. NED Vol. 362 (2020)

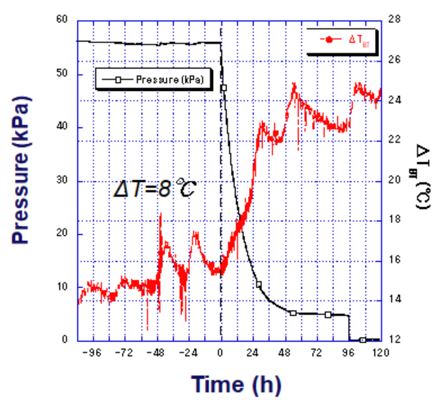


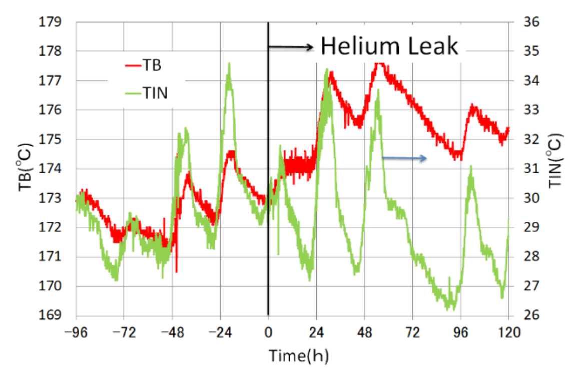




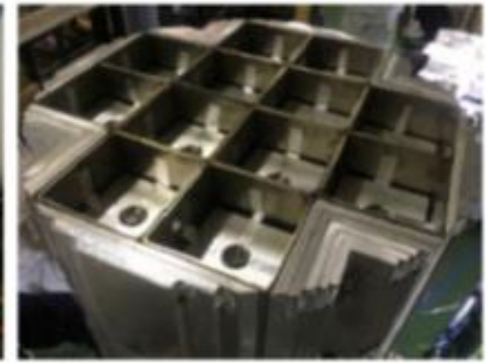
$$\Delta \ T_{BT} = T_B - T_T$$

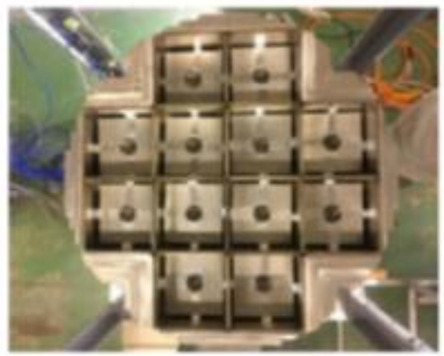


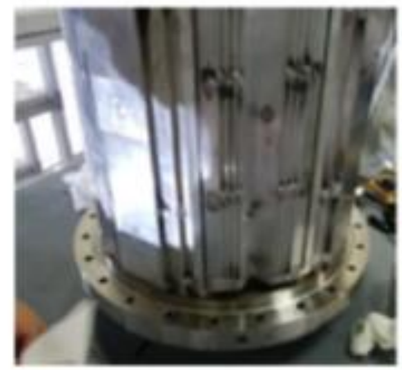




1/4.5-Scale Model Cask



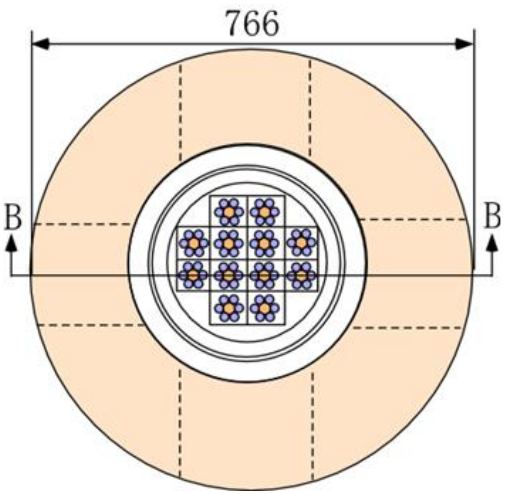


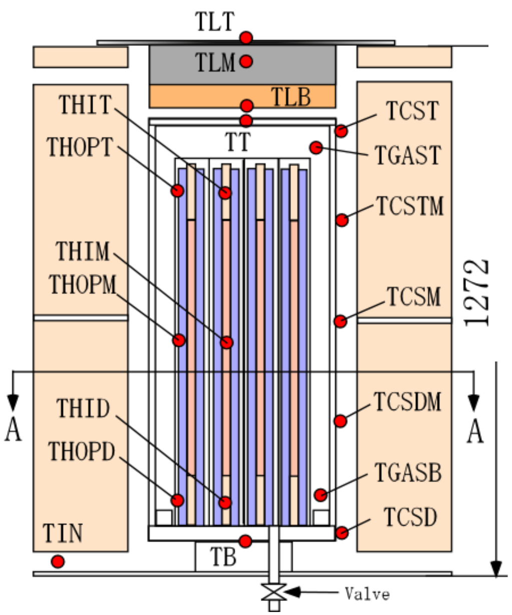


- Based on T-H similarity law with independent control of test parameters
  - Decay heat load (up to 90 years of dry storage)
  - Fill-gas (air and helium) and pressure (up to 6 atm)
  - Instrumentation (power, pressure, and temperature)
  - Controlled leakage path (size of simulated CISCC crack) and start of leakage

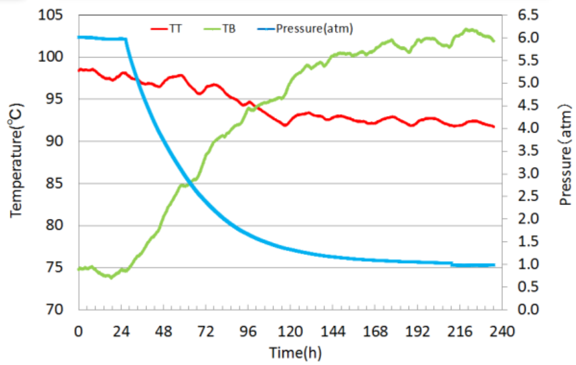
Evaluation of Leak Detection by ΔTBT Method

1/4.5-Scale Cask Model



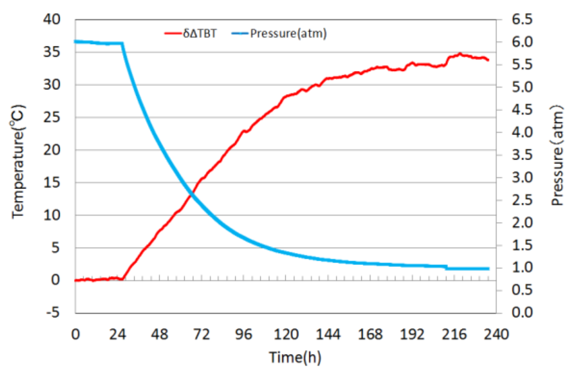


TT, TB vs. Pressure



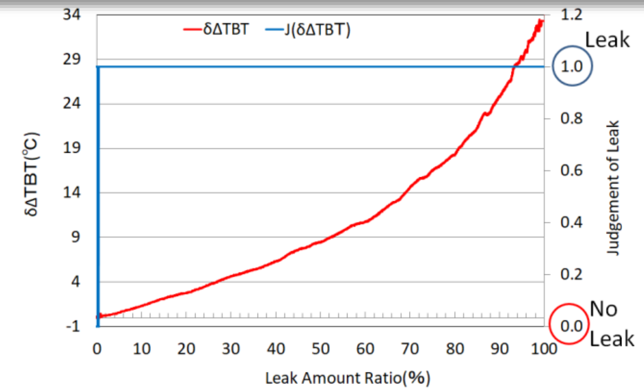
ΔTBT vs. Pressure

$$\Delta T_{BT} = T_B - T_T$$



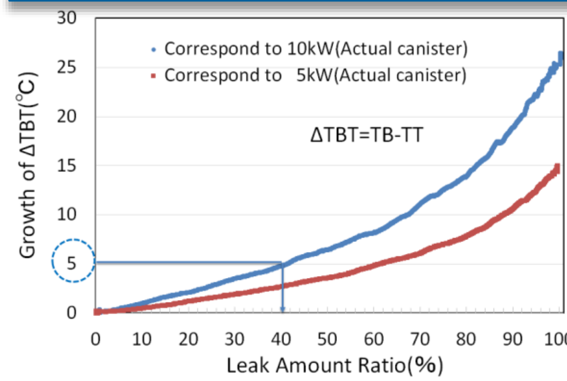
The actual temperature can be calculated from the test results by the transform expression.

Leak Amount Ratio vs. ΔTBT



The leak amount ratio of 0.5% (2 kPa) could be detected in the laboratory tests.

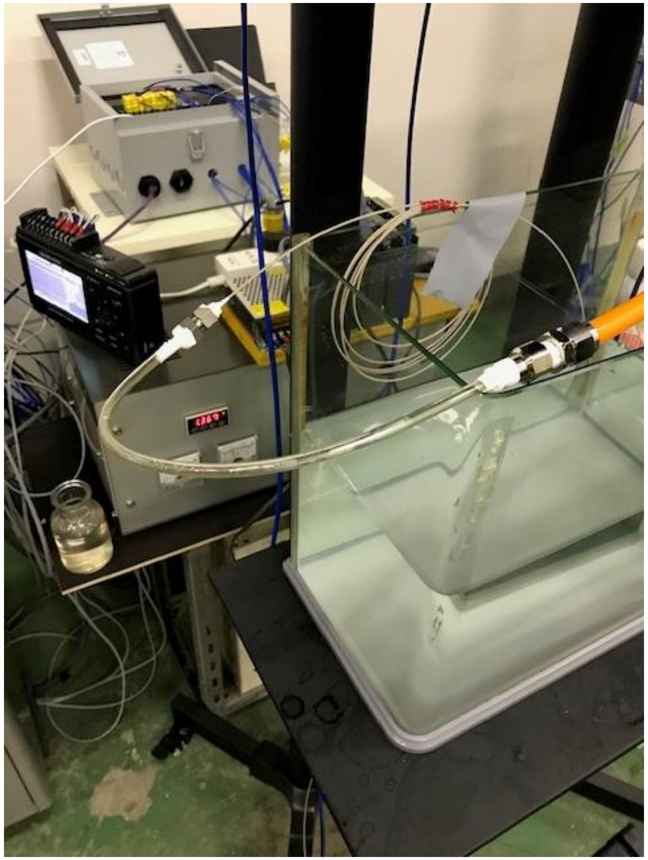
Actual Canister Evaluation



$$\frac{\Delta T_p}{\Delta T_m} \equiv \left(\frac{\xi_p}{\xi_m}\right)^{\frac{1}{3}} \left(\frac{\beta_p \rho_p^2 c_p^2}{\beta_m \rho_m^2 c_m^2}\right)^{-\frac{1}{3}} \left(\frac{L_p}{L_m}\right)^{-\frac{5}{3}} \left(\frac{Q_p}{Q_m}\right)^{\frac{2}{3}} \equiv \left(\frac{\rho_p^2 c_p^2}{\rho_m^2 c_m^2}\right)^{-\frac{1}{3}} \left(\frac{L_p}{L_m}\right)^{-\frac{5}{3}} \left(\frac{Q_p}{Q_m}\right)^{\frac{2}{3}} = 0.76$$

Gas Leakage Path and "Simulated" CISCC Crack

Small-diameter pipelet with varying lengths

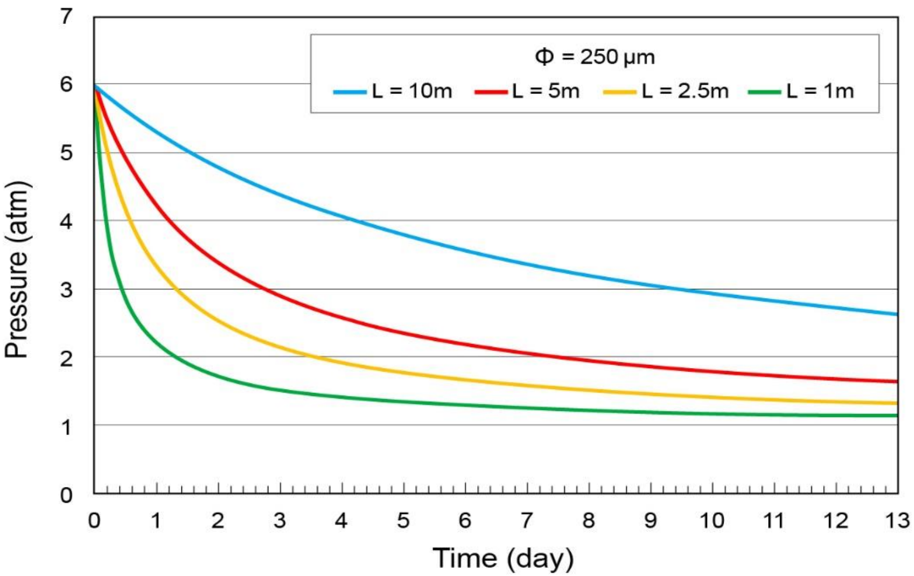


ANSI N-14.5 volumetric leakage rate

$$L_u = (F_c + F_m)\,(P_u - P_d)\,(P_a/P_u)$$

$$F_c = [2.49 \times 10^6\, D^4] / (a\,\mu)$$

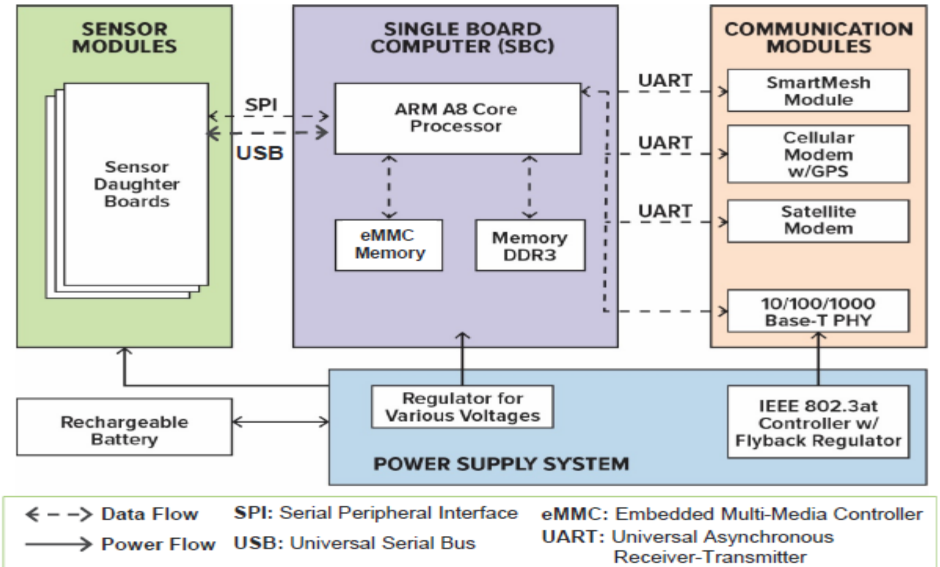
$$F_m = [3.81 \times 10^3\, D^3\, (T/M)^{0.5}] / (a\,P_a)$$



CISCC "equivalent" pinhole diameter of 45.8–47.1 µm can be derived assuming crack length = wall thickness (e.g., 0.5 in.) of MPC of actual dry storage system

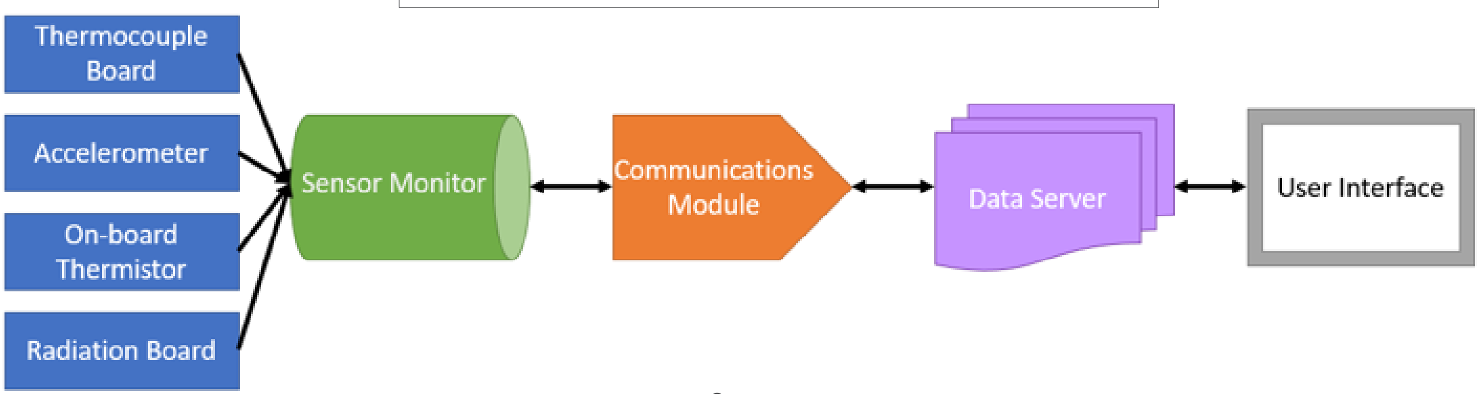
Remote Area Modular Monitoring (RAMM) for Temperature Measurement (RAMM-TM)

Functional Block Diagram of RAMM

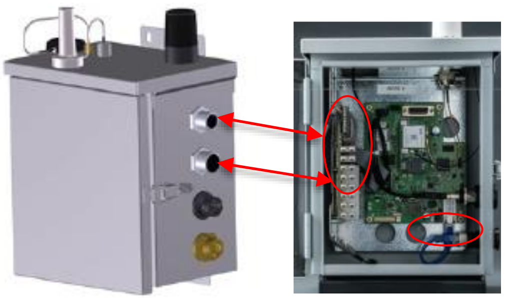


Edge computing

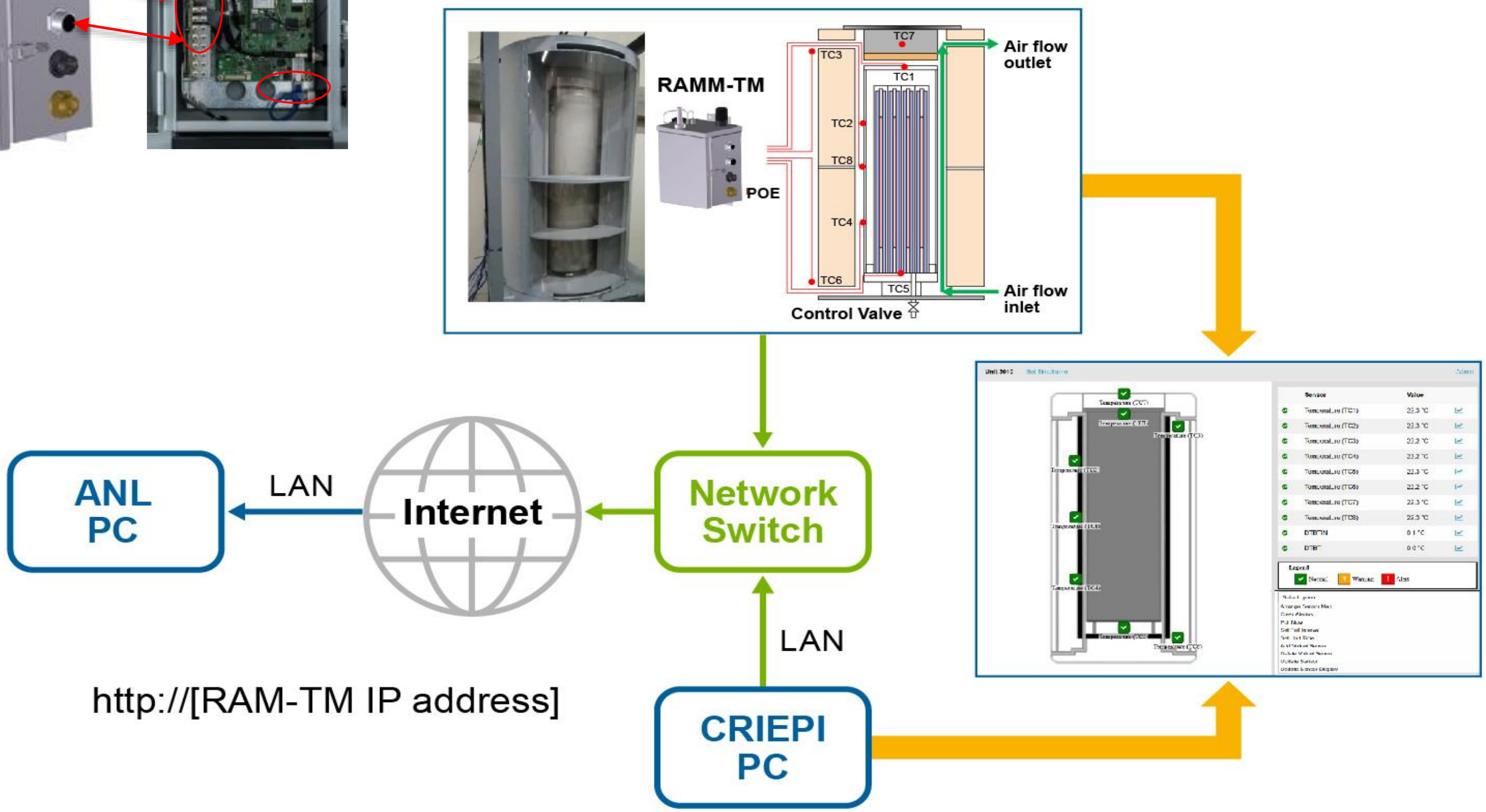
Customized “Stand-alone” RAMM-TM



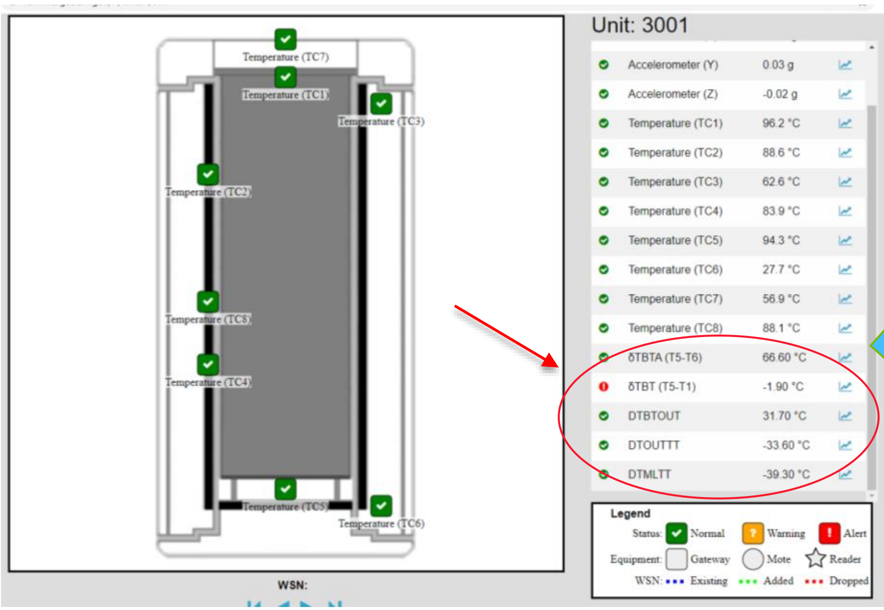
RAMM-TM Data Flows during Gas Leakage Experiment



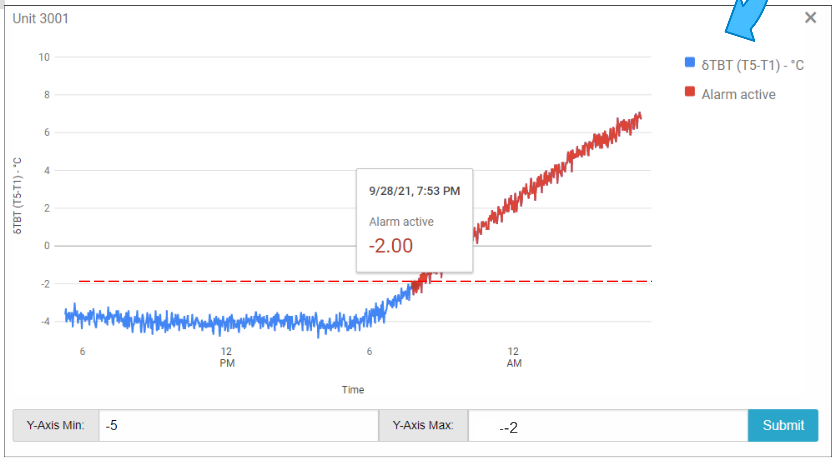
Data sharing between Argonne (Chicago) and CRIEPI (Tokyo) in real time



Web Application User Interface and “Virtual Sensors” (analytical functions of data measured by physical sensors – i.e., TCs)

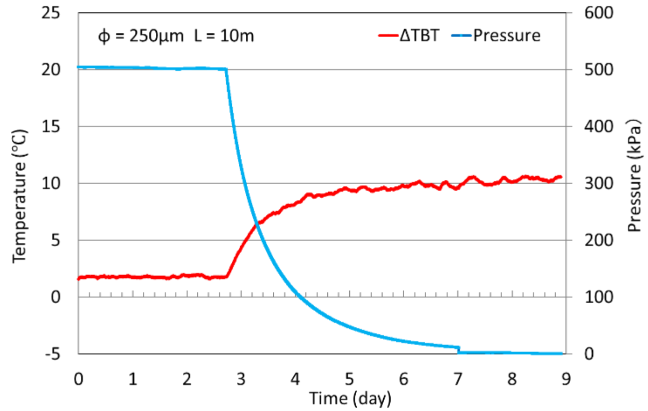


- δTBTA (TC5 – TC6)
- **δTBT (TC5 – TC1)**
- DTBTOUT (TC5 – TC3)
- DTTOUT (TC1 – TC3)
- DTMLTT (TC7 – TC1)

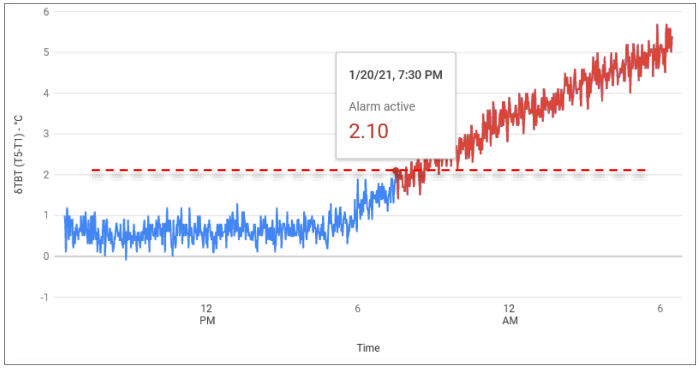


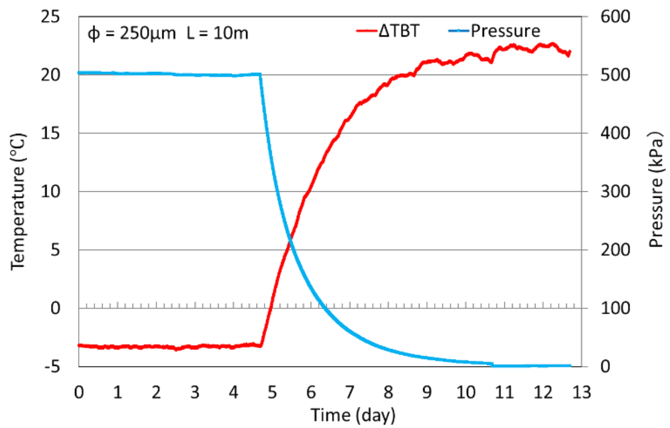
- Adjustable alarm thresholds
- Automatic alarms and notifications

Gas Leakage Depressurization, ΔTBT, and Alarms

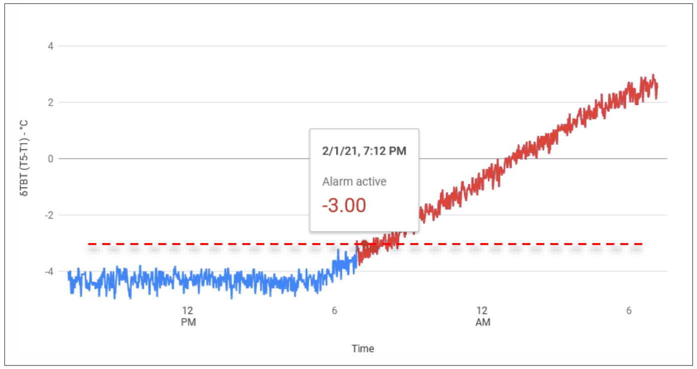


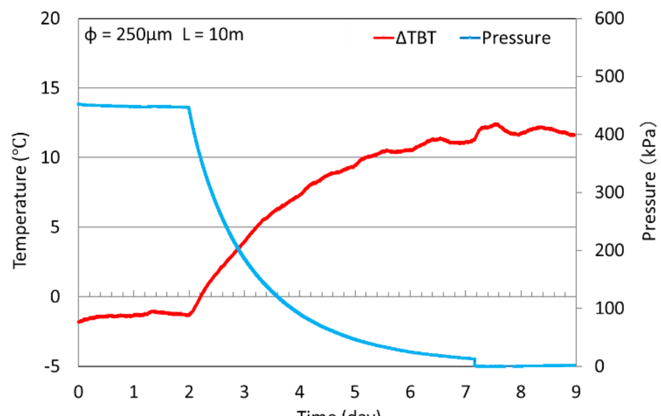
He/391W



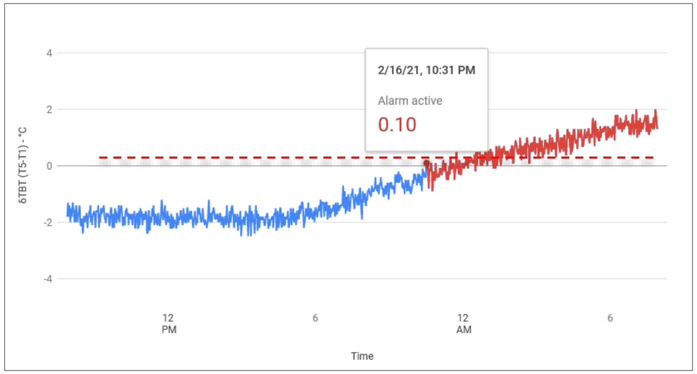


Air/385W

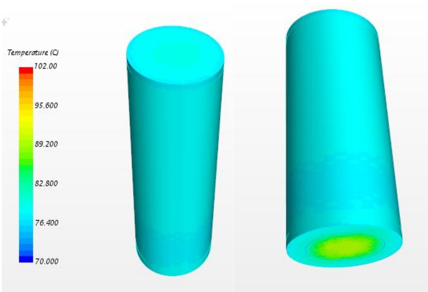




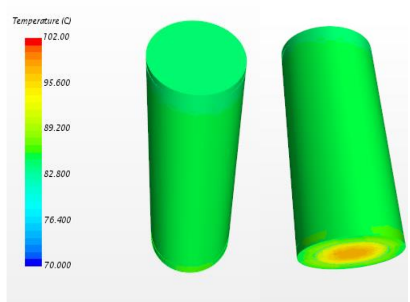
Air/189W



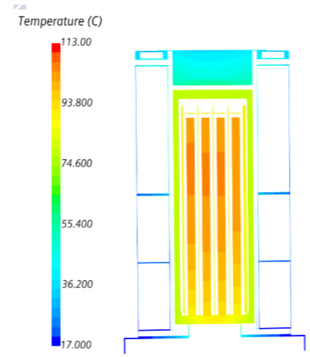
STAR-CCM+ simulation [395W/He; (a): 6 atm/(b) 1 atm]



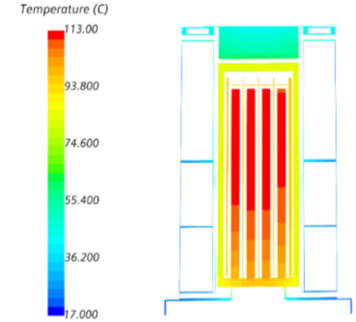
(a)



(b)

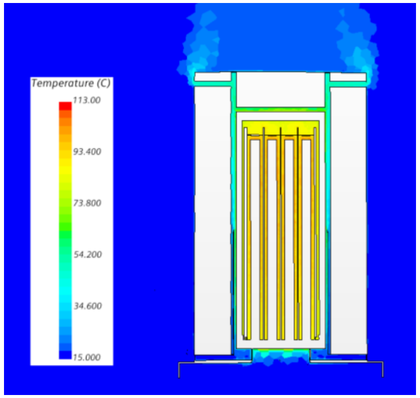


(a)

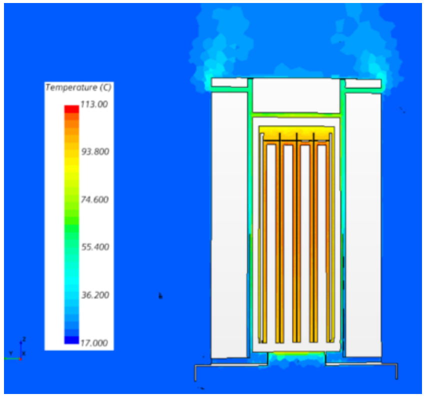


(b)

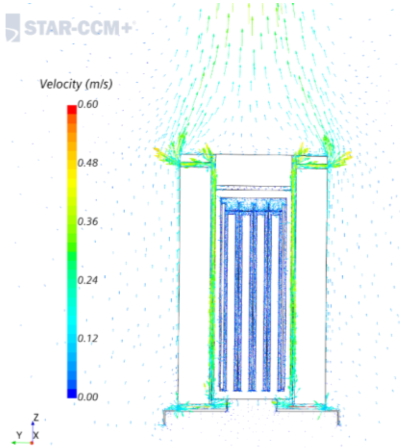
- Each simulation employed ~5 million elements, executed on 32-core parallel machine at Argonne's Laboratory Computing Research Center (LCRC).
- Based on study of residuals of energy, continuity, X-, Y-, and Z- momentum, and turbulence T_{dr} (vortex) and T_{ke} (kinetic energy), convergence was achieved after 18,000 iteration steps with 3.1 s/step.



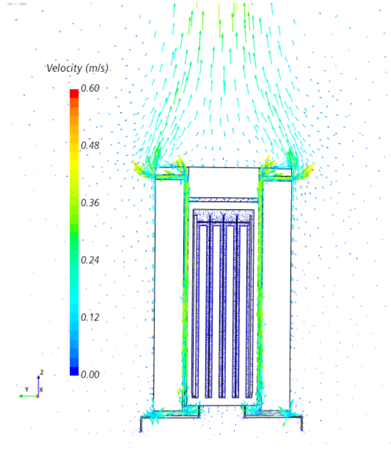
(a)



(b)

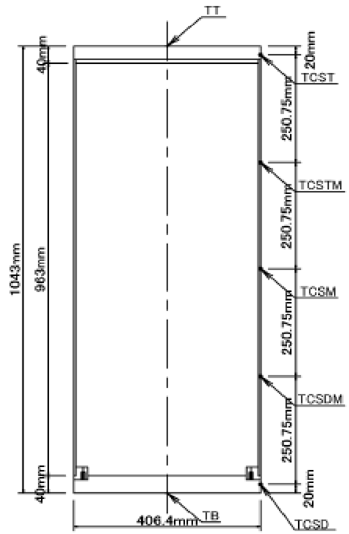


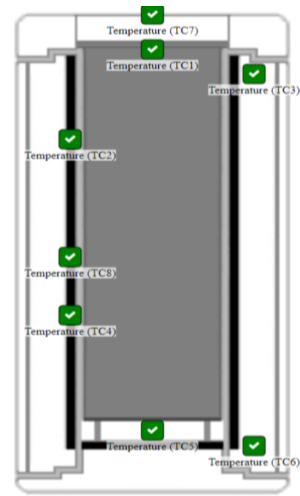
(a)



(b)

STAR-CCM+ Simulation vs. Temperature Measurement in 1/4.5-Scale Model Cask (394W/air)

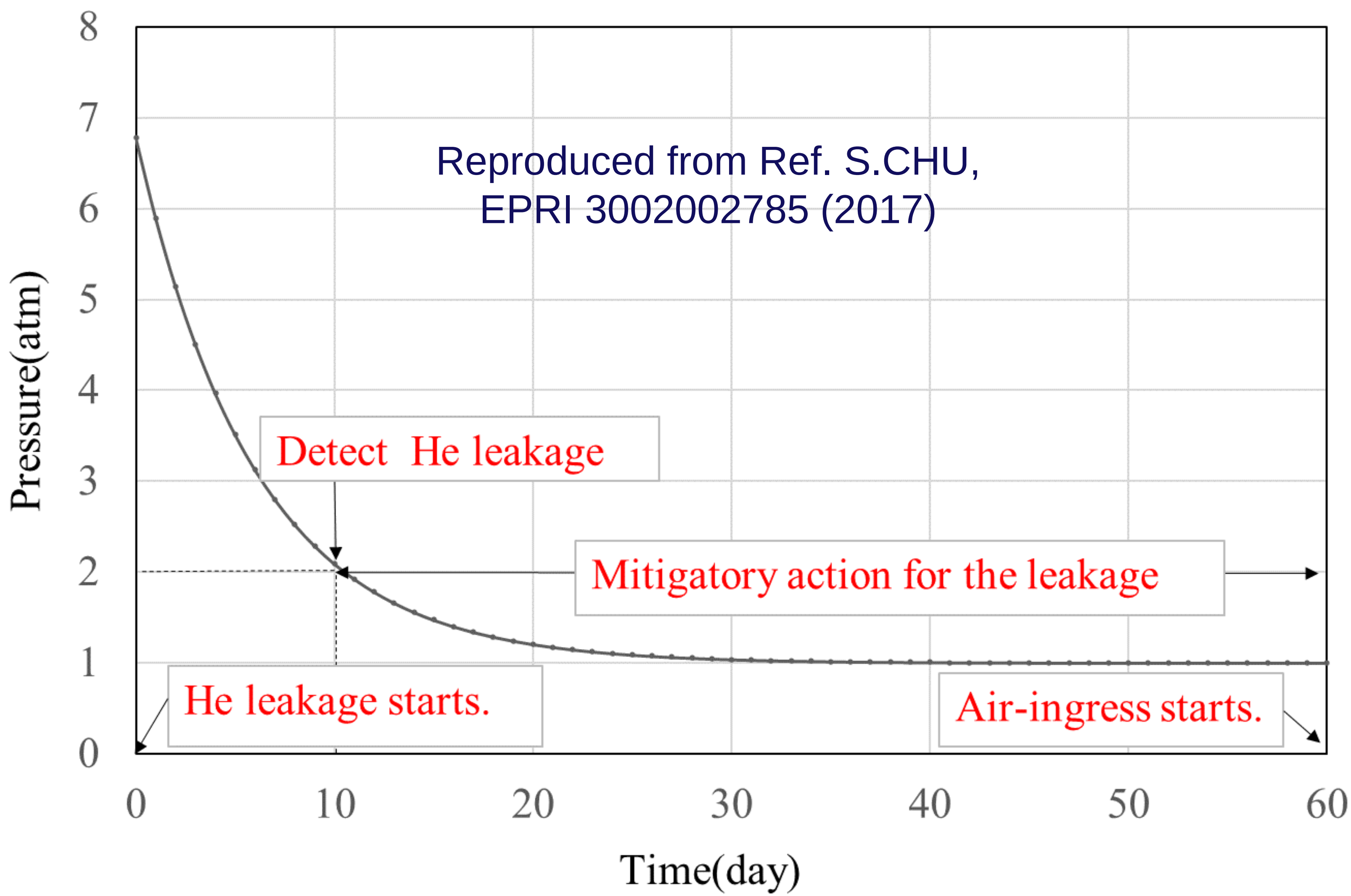




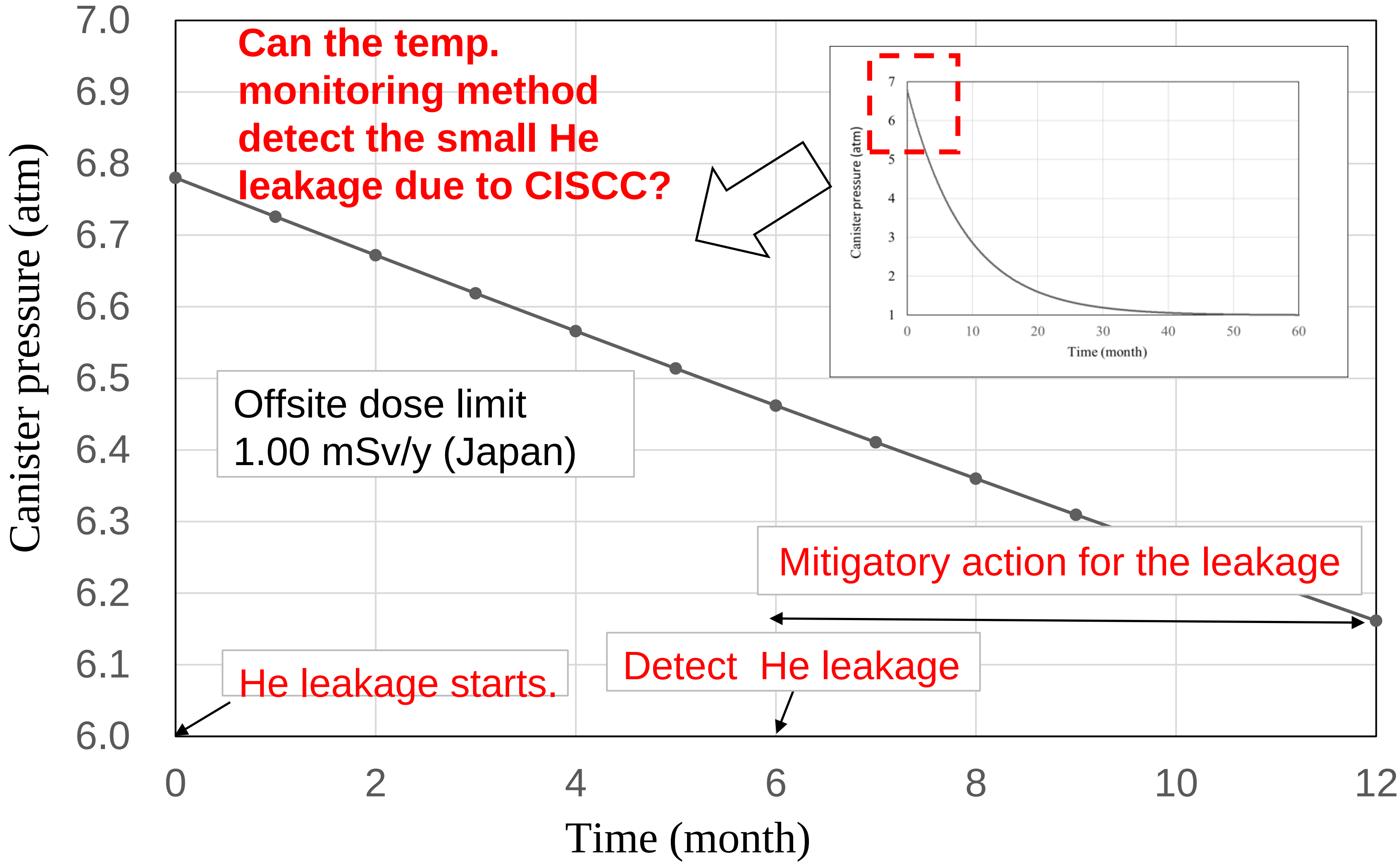
Thermocouple Locations (h)	Calc. Temp. (°C)		Exp. Temp. (°C)	
	6 atm	1 atm	6 atm	1 atm
Canister top center, TT (TC1)	82.7	80.7	92.0	85.1
Canister wall, h=0.78, TCSTM/TC2	80.3	80.4	82.7	80.4
Canister wall, h=0.52, TCSM/TC8	80.4	81.1	81.5	83.1
Canister wall, h=0.26, TCSDM/TC4	81.0	82.5	78.3	80.6
Canister bottom center, TB (TC5)	102.8	109.4	87.4	103.0

*h = z/H where H = 1048 mm

Radiological Consequences of Gas Leakage (Pressure Drop) due to CISCC (Scenario 1)



Radiological Consequences of Gas Leakage (Pressure Drop) due to CISCC (Scenario 2)



Conclusions

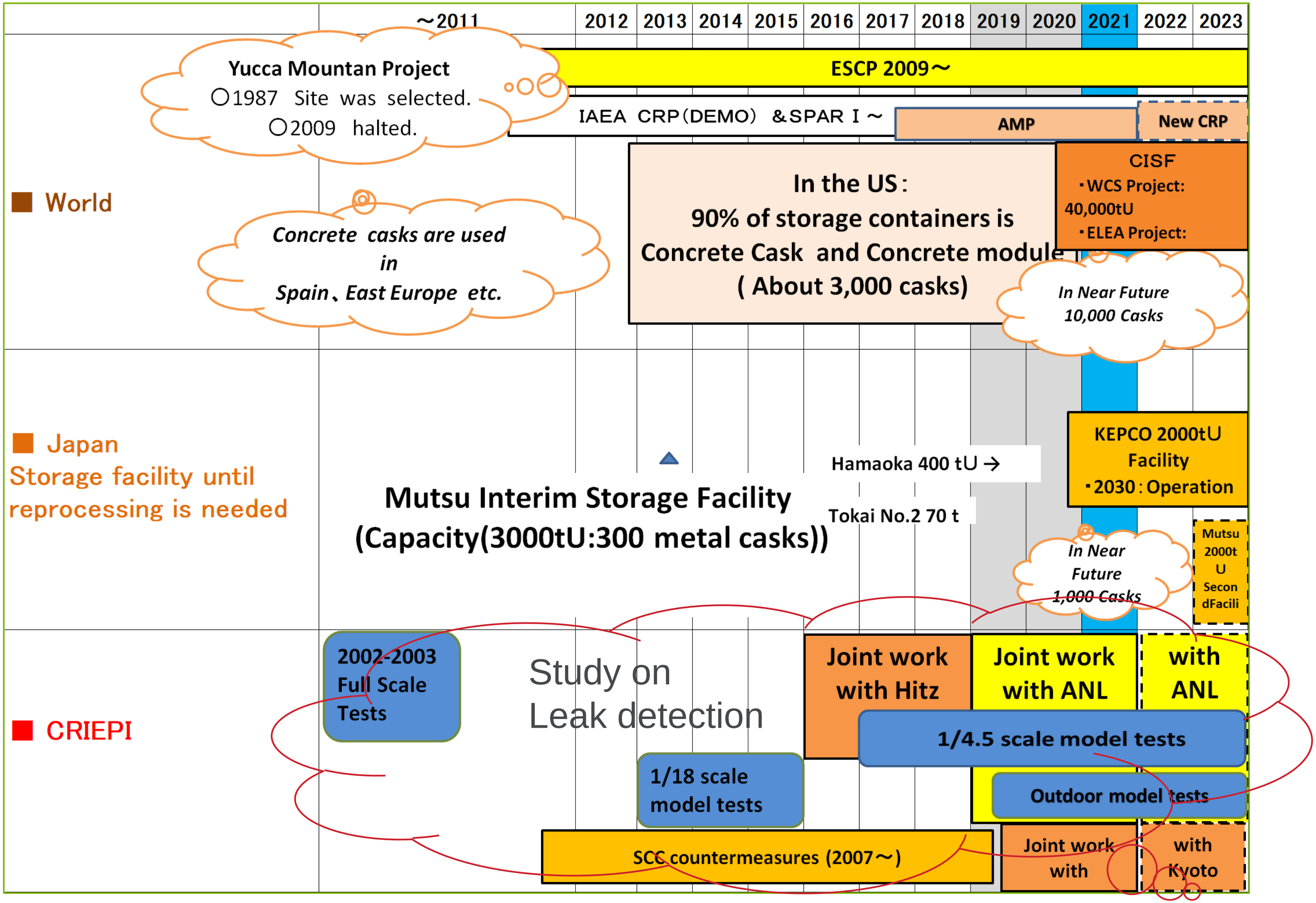
- Both helium and air gas leakage from a canister were detected within hours after the start of the leakage. The change in ΔTBT during gas leakage (depressurization) triggered automatic alarms, providing a sound basis for early detection of gas leakage from the canister.

- This methodology would allow consequence management through the implementation of mitigatory actions to continue effective aging management and to reduce risks to public safety, health, and the environment.

- Additional gas-leakage experiments are being conducted to explore the use of multiple “Virtual Sensors” for gas-leakage detection and for confirmation of gas leakage in actual spent-fuel canisters.

- STAR-CCM+ simulation of temperatures, density, and flow fields inside and outside the canister will continue to deepen the understanding of gas leakage and thermal response in actual MPCs of spent-fuel dry cask storage systems.

Current Status of Spent Fuel Storage



QUESTIONS?

Acknowledgment

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9. Toshiari Saegusa, Hirofumi Takeda, Yung Liu, “Monitoring of helium gas leakage from canister storing spent nuclear fuel: Radiological consequences and management,” Nuclear Engineering and Design 382 (2021) 111391.
10. Yung Liu, Brian Craig, Zenghu Han, Jie Li, Kevin Byrne, Hirofumi Takeda, and Toshiari Saegusa, “RAMM-TM for detection of gas leakage from canisters containing spent nuclear fuel,” Nuclear Engineering and Design 385 (2021) 111534.

Backup Slides

Setting ΔTBT Alarm Thresholds